Measuring Geosynchronous Satellites from Stellar Appulses with AO[1]

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ABSTRACT

Testing our ability to study geosynchronous satellites using adaptive optics on our 3.5 m telescope with a Laser Guide Star (LGS) and without a laser (Natural Guide Star, NGS), we found two satellites in the same small $25'' = 125$ μrad field of view (FOV) over a period of 7.5 minutes using only NGS. Only by tracking our intended target for 23 minutes were we able to ultimately disentangle the objects when they were in the same FOV by comparing trajectories. In addition, over the 23 minutes of intermittent imaging we identified and measured seven background stars as they trailed by, with four others too faint to measure at this time. These stars provided reference positions and magnitudes for the satellites. Overall, we demonstrate that we can time appulses of stars and geosynchronous satellites to an accuracy of 0.33 sec, and positions to $0.067''$ with respect to the RA and Dec of stars.

1. Background

Using a laser to produce a Laser Guide Star (LGS) for high order adaptive optics (AO) corrections allows fainter objects to be studied as compared to Natural Guide Star (NGS) work. To test how well NGS AO can perform in the brightness regime of geosynchronous satellites (geos), we slowed the AO loop by a factor of 8 to 250 Hz, thereby sacrificing Strehl. In addition, we diverted light intended for an I band science camera to the wave front sensor, and only imaged in the J band at 1.2 μm. Complicating any attempts to make precise measurements of geo positions or brightness is the fact that since geos are stationary against the background of stars, only an occasional background streak can be seen from a star as it moves past at the sidereal rate. Nevertheless, we show that these close approaches, or appulses, can be used for such precise measurements.

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14. ABSTRACT
Testing our ability to study geosynchronous satellites using adaptive optics on our 3.5 m telescope with a Laser Guide Star (LGS) and without a laser (Natural Guide Star, NGS), we found two satellites in the same small 25??????= 125 rad field of view (FOV) over a period of 7.5 minutes using only NGS. Only by tracking our intended target for 23 minutes were we able to ultimately disentangle the objects when they were in the same FOV by comparing trajectories. In addition, over the 23 minutes of intermittent imaging we identified and measured seven background stars as they trailed by, with four others too faint to measure at this time. These stars provided reference positions and magnitudes for the satellites. Overall, we demonstrate that we can time appulses of stars and geosynchronous satellites to an accuracy of 0.33 sec and positions to 0.067?????? with respect to the RA and Dec of stars.

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2. Observations

On 2014 January 13, with our 3.5 m telescope using NGS AO, we targeted a geo, satellite 28868 ANIK F1-R, for study. We imaged it intermittently for 23 minutes, noticing 7 passing stars in 43 frames in 7 sets of 1000 frame bursts. The first two sets of 1000 frames were made with exposure times of 2 ms each, and the next five were made with 20 ms exposure times. When we returned to the third set of images, we found another satellite in the field and followed them together on the third through sixth sets, until they were too far apart on the last set.

2.1. Relative to True Positions

Each star can be seen on 3-10 successive images as short streaks. Each streak, along with the one or two satellites in the frame, is fit as an elongated Gaussian. This Gaussian fit yields, among other parameters, the objects' X and Y centers. A straight line trajectory of the star streak positions $[X_t; Y_t]$ is calculated with respect to the star at $[X_*; Y_*]$

$$a(X_t - X_*) + b(Y_t - Y_*) = 1 \quad , \qquad 1$$

and a single position of closest approach to the star is calculated by constructing a perpendicular from the trajectory to the star

$$Y_\perp = Y_* + b/a(X_\perp - X_*) \quad . \qquad 2$$

The intersection of the perpendicular and the trajectory of streaks marks the appulse, the point of minimum approach, when the star passes due south or north of the satellite,

$$X_0 = a/(a^2 + b^2) \; ; Y_0 = b/(a^2 + b^2) \qquad 3$$

at a distance of $d = \sqrt{X_0^2 + Y_0^2} = 1/\sqrt{a^2 + b^2}$. From the RA_* and Dec_* of the known star, the position of the satellite at minimum approach is then RA_* and $Dec_* \pm d$, depending on whether the appulse of the star was north or south of the satellite.

The seven stars, once identified, then provide seven accurate positions in 23 minutes to plot a trajectory in RA and Dec. However, identifying the stars can be difficult. Unless the position of all the components of the optics are recorded for each observation against the telescope pointing coordinates, and only then if the star streaks can be timed accurately and absolutely, can ambiguities in matching these faint stars to catalogs be resolved. Our facility's ability to time stamp all components to better than 1 ms on an absolute scale greatly aids in this surprisingly difficult task for our small FOV.

Although many star catalogs are available to search, even by hand, we have found that the US Naval Observatory's web site is particularly useful. At `http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/icas/vo_nofs` several catalogs have been combined into one source called The Naval Observatory Merged Astrometric Dataset or NOMAD, which can be searched or filtered. Our seven stars were identified this way, and accurate positions (and times) for both satellites are calculated. Figure 1 shows the trajectories of the two satellites through a field of stars. Initially, in the frames where the two satellites appeared together, we assumed that the one that first appeared nearest the center of the image was the target 28868. Not until we plotted all of the positions (Figure 1), did we conclude that the satellite identities were reversed.

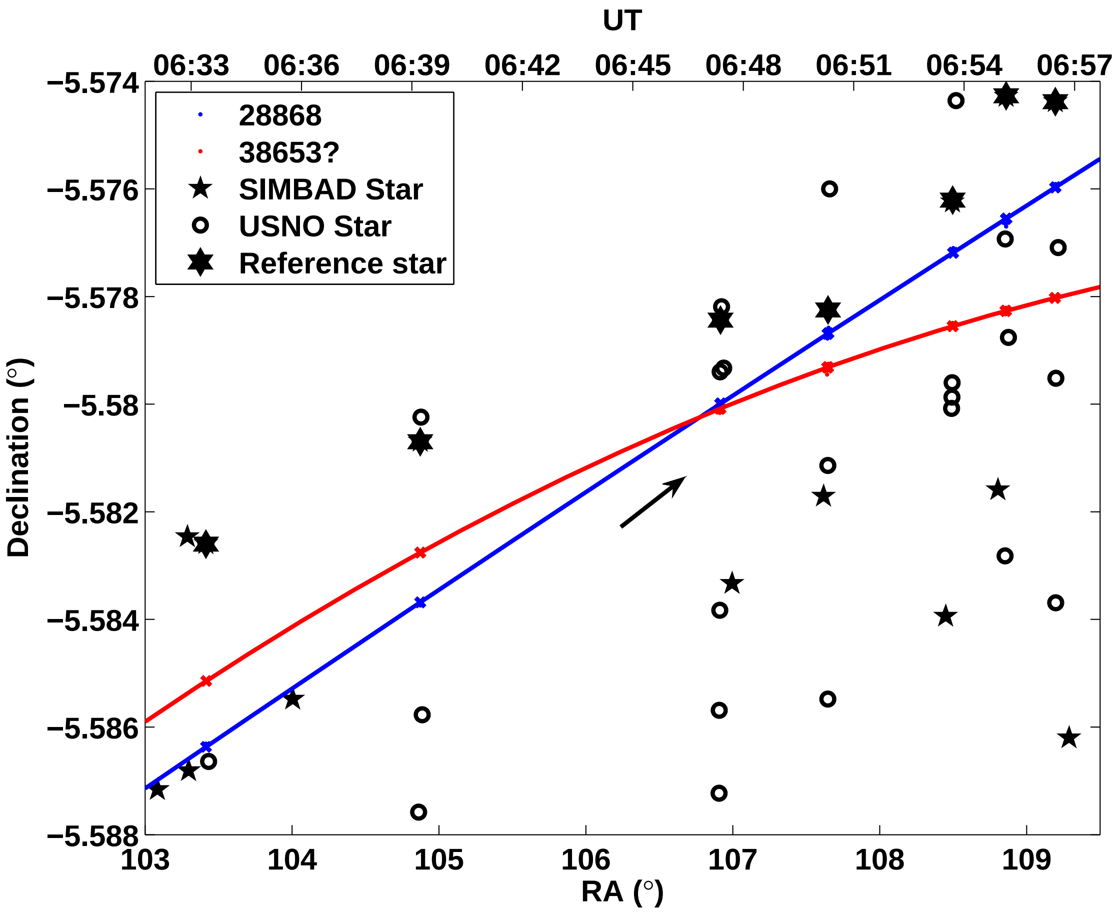

Fig. 1.— Trajectories of two satellites. The positions of two satellites are plotted against some candidate catalog stars at seven times when the satellite passed closest to a star. In 4 of the 7 sets of 1000 frames, two satellites were visible. Our target was satellite 28868 in blue, and we have tentatively identified the passing satellite (red) as the rocket body 38653. Initially, however, we had their identities reversed because the rocket body appeared in the center of the images. Not until we plotted the positions as depicted here were we able to make the correct assignment.

2.2. A Passing Satellite

As a separate project, we calculated the trajectory of the untargeted satellite with respect to satellite 28868 and show it in Figure 2. Fitting the relative positions of the untargeted satellite as a linear function of time, Table 1 encapsulates the velocity between the two objects at the moment of close approach. Considering the distinct difference in relative motion, we have tentatively identified the passing object as satellite 38653, a rocket body in the vicinity of our target on this night.

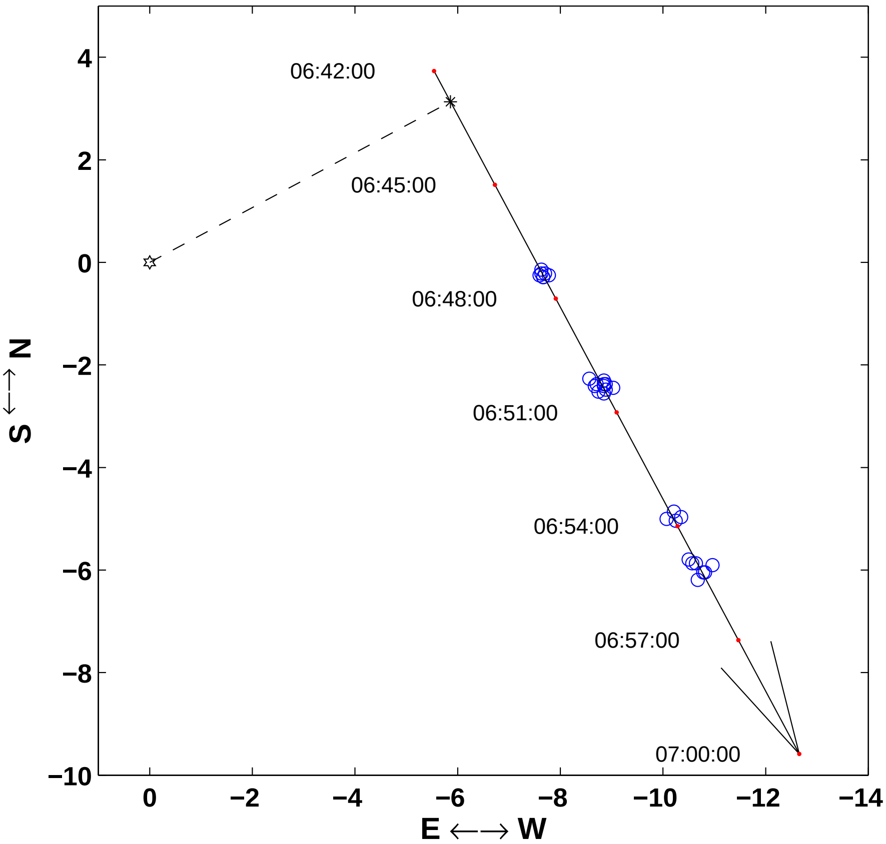

Fig. 2.— Close approach of two satellites. Plotting the 29 positions (blue circles) of the unknown object with respect to satellite 28868 placed at [0,0], we can calculate its closest approach at the perpendicular to the apparent path. Scale is in arcseconds. The particulars are given in Table 1.

Table 1. Closest approach of an unknown to satellite 28868
2014 Jan 13 6.7135±0.0022 UT

Quantity	Magnitude	Direction
Position	6.643±0.065 $''$	$298.1^\circ \pm 0.5^\circ$ (NW)
Velocity	50.3±0.4 $''$/hr	$208.1^\circ \pm 0.5^\circ$ (SW)

3. Differential Photometry

Finally, since the seven reference stars all have J magnitudes listed, and since they are in the same small FOV, we can obtain relative magnitudes of the two satellites with respect to the stars, even through clouds as was the case here. Once the stars and satellites are fit as two dimensional Gaussians, their volumes fall out analytically and their ratios yield their magnitudes. Figure 3 shows the means and errors of the mean of the satellite J magnitudes as determined from the 3-10 streaks for each frame where the relevant objects were in the same field. Also shown are the magnitudes of the reference stars taken from the USNO NOMAD catalog at `http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/nomad`.

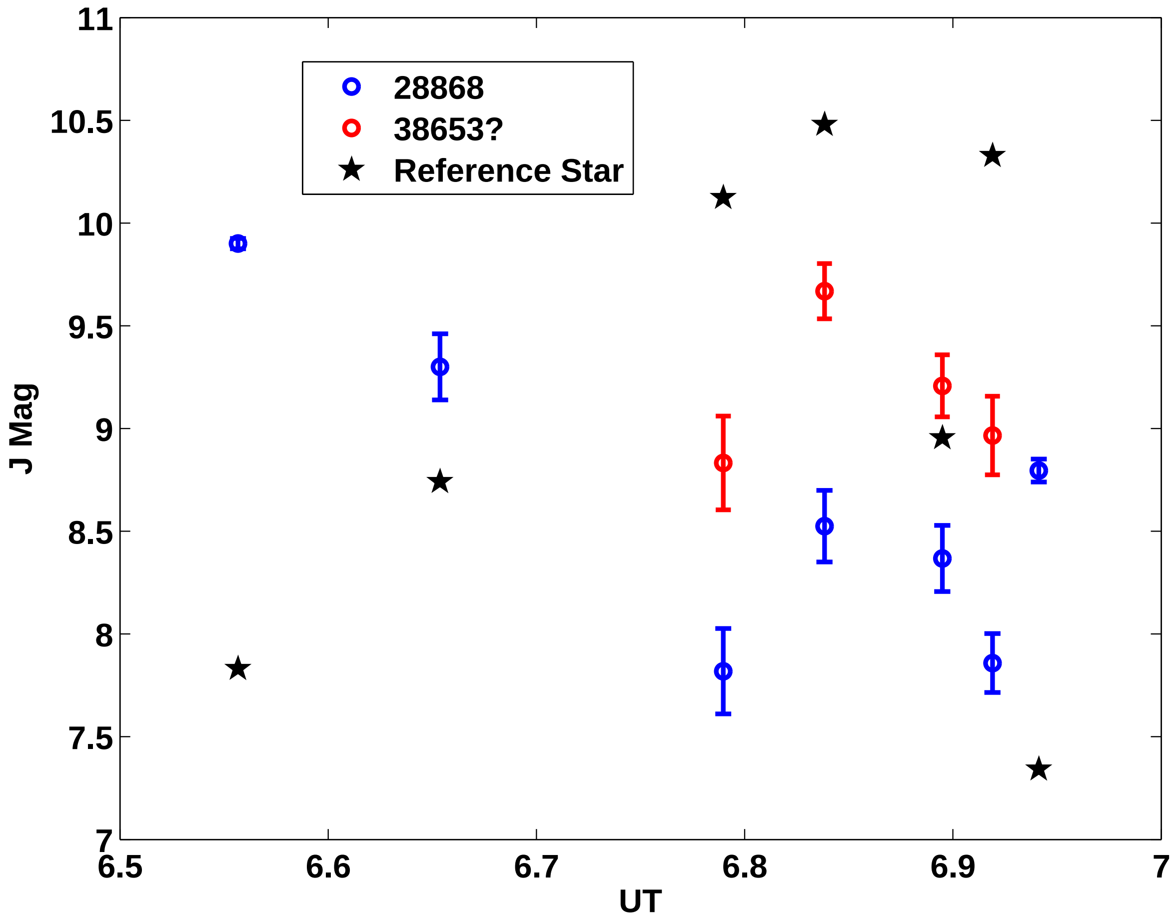

Fig. 3.— J magnitudes from differential photometry. Magnitudes for the reference stars are taken from the US Naval Observatory's NOMAD catalog. The satellite magnitudes are then measured with respect to these stars when they are in the same field of view, all summarized in Table 3.

4. Summary Results

Table 2 contains the times, positions and magnitudes of the two satellites. While the reference stars have both J and V magnitudes listed, we can calculate the V magnitudes of the satellite by assuming that they show solar colors, for which V magnitudes are 1.1 magnitudes fainter than J magnitudes.

Table 2. Position and Magnitudes of Satellites
2014 Jan 13

UT	RA	Dec	J	V	Ref Star #
		Sat 28868			
6.556728	103.41502	-5.58634	9.90±0.03	11.00	1
6.653712	104.87330	-5.58372	9.30±0.16	9.94	2
6.789600	106.91659	-5.58001	7.82±0.21	8.92	3
6.838272	107.64840	-5.57866	8.52±0.17	9.63	4
6.894792	108.49633	-5.57724	8.37±0.16	9.47	5
6.918912	108.86125	-5.57662	7.86±0.14	8.96	6
6.941184	109.19593	-5.57595	8.80±0.06	9.90	7
		Sat 38653?			
6.789744	106.91659	-5.58008	8.83±0.23	9.93	3
6.838416	107.64841	-5.57929	9.67±0.13	10.77	4
6.894888	108.49634	-5.57852	9.21±0.15	10.31	5
6.919104	108.86126	-5.57824	8.97±0.19	10.07	6

Table 3. Position and Magnitudes of Reference Stars

Ref #	USNO Name	RA	Dec	J	V
1	0844-0110369	103.41501	-5.58260	7.832	9.761
2	0844-0115517	104.87328	-5.58070	8.742	9.299
3	0844-0124099	106.91659	-5.57844	10.124	11.35
4	0844-0127537	107.64839	-5.57825	10.48	12.29
5	0844-0131537	108.49629	-5.57624	8.955	11.579
6	0844-0133248	108.86121	-5.57428	10.328	10.48
7	0844-0134716	109.19591	-5.57438	7.342	10.518

These results demonstrate that high accuracy position measurements can be made on geosynchronous satellites in NGS mode since passing background reference stars leave short but measurable streaks in successive 5-20 ms frames. The mean error in determining the time of an appulse from the 11 cases (7 for satellite 28868 and 4 for 38653) is 0.33 sec, and the error in determining the appulse distance, and therefore position, is $0.067''$.

The small field of view also allows differential photometry to be performed even through clouds. While large sky area coverage with wide field cameras can gather more stars to calculate astrometric positions, our small FOV work produces precise measurements against the fewer stars that pass by during appulses, even in frames as short as 5 ms. Furthermore, the small FOV has the added advantage of providing photometric measurements in less than ideal conditions.